

Exploring the dark accelerator HESS J1745-303 with *Fermi* Large Area Telescope

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ABSTRACT

We present a detailed analysis of the γ -ray emission from HESS J1745-303 with the data obtained by the *Fermi* Gamma-ray Space Telescope in the first ~ 29 months observation. The source can be clearly detected at the level of $\sim 18\sigma$ and $\sim 6\sigma$ in $1 - 20$ GeV and $10 - 20$ GeV respectively. Different from the results obtained by the *Compton* Gamma-ray Observatory, we do not find any evidence of variability. Most of emission in $10 - 20$ GeV is found to coincide with the region C of HESS J1745-303. A simple power-law is sufficient to describe the GeV spectrum with a photon index of $\Gamma \sim 2.6$. The power-law spectrum inferred in the GeV regime can be connected to that of a particular spatial component of HESS J1745-303 in $1 - 10$ TeV without any spectral break. These properties impose independent constraints for understanding the nature of this “dark particle accelerator”.

Subject headings: supernova remnants — gamma-rays: individual (HESS J1745-303, 3EG J1744-3011, G359.1-0.5)

1. INTRODUCTION

Recent surveys of the central region of our Galaxy with the **H**igh **E**nergy **S**teroscopic **S**ystem (H.E.S.S.) have uncovered a number of γ -ray sources in the TeV regime (Aharonian et al. 2002, 2005a, 2005b, 2006a). Different from the cases of pulsar wind nebulae (PWNe) and young supernova remnants (SNRs), some of these sources have no non-thermal X-ray counterpart yet been identified. Among them, HESS J1745-303 is one of the most enigmatic objects.

HESS J1745-303 was firstly discovered by the H.E.S.S. Galactic Plane Survey (Aharonian et al. 2006a) and was subsequently investigated in details with dedicated follow-up observations (Aharonian et al. 2008). The TeV γ -ray image shows that it consists of three spatial components (i.e. Regions A, B and C in Fig. 1 of Aharonian et al. 2008). Owing to the lack of spectral variability and the insignificant dip among these regions in the existing data, it was argued that they are originated from a single object (Aharonian et al. 2008). This inference suggests that HESS J1745-

303 as one of the largest unidentified TeV sources which has an angular size of $\sim 0.3^\circ \times 0.5^\circ$.

Searches for the possible non-thermal diffuse X-ray component in region A of HESS J1745-303 have been conveyed with *XMM-Newton* and *Suzaku* (Aharonian et al. 2008; Bamba et al. 2009). None of these observations have resulted in any evidence for the diffuse X-ray emission. This imposes a TeV-to-X-ray flux ratio larger than ~ 4 (Bamba et al. 2009) which is larger than the typical value of PWNe and SNRs (i.e. less than 2) (cf. Matsumoto et al. 2007; Bamba et al. 2007, 2009). Because of the non-detection of counterparts in X-ray/radio, HESS J1745-303 is dubbed as a “dark accelerator” (Bamba et al. 2009).

While no non-thermal diffuse X-ray emission has yet been found, a possible excess of neutral iron line emission was discovered in the direction toward the region A of HESS J1745-303 (Bamba et al. 2009). Together with its proximity to the Galactic center and the positional coincidence of a molecular cloud (Aharonian et al. 2008), the line emission is suggested to be the reflected X-rays originated from the previous activity in the

Galactic center (Bamba et al. 2009). This molecular cloud can be interacted with the shock from a nearby SNR G359.1-0.5 (Bamba et al. 2000, 2009; Lazendic et al. 2002; Ohnishi et al. 2011) and produce the observed γ -rays through the acceleration of protons and/or leptons (see Bamba et al. 2009). Nevertheless, this proposed scenario cannot be confirmed unambiguously. In view of the presence of many surrounding objects (see Fig. 1 in Aharonian et al. 2008), including the “mouse” pulsar (i.e. PSR J1747-2958), one cannot rule out these objects as the source of energetic particles simply based on the TeV results (Aharonian et al. 2008). Furthermore, with the current information, it is not possible to discriminate hadronic model and leptonic model (see Fig. 5 & 6 in Bamba et al. 2009). In order to do so, investigations in lower energy regime are required.

It is interesting to note that HESS J1745-303 is positionally coincident with an unidentified EGRET source 3EG J1744-3011 (Hartman et al. 1999). Different from HESS J1745-303, 3EG J1744-3011 was suggested to demonstrate long-term variability (Torres et al. 2001). Also, based on the MeV-GeV spectrum observed by EGRET, the extrapolated flux in the TeV regime overshoots that observed by H.E.S.S.. Therefore, Aharonian et al. (2008) considered that 3EG J1744-3011 is unrelated to HESS J1745-303.

After the commence of the Large Area Telescope (LAT) onboard *Fermi* Gamma-ray Space Telescope, a detailed investigation of this dark accelerator in the MeV–GeV regime is now feasible with its much improved spatial resolution and sensitivity. However, among 1451 objects detected by LAT during the first 11 months, we do not identify any source corresponding to HESS J1745-303 / 3EG J1744-3011 (Abdo et al. 2010). Very recently, in an analysis of the γ -rays from the Galactic center with first 25 months LAT data, a new serendipitous source was found to coincide spatially with HESS J1745-303 / 3EG J1744-3011 (Chernyakova et al. 2011). In this paper, we report a detailed analysis of this source with LAT observation in the first ~ 29 months.

2. DATA ANALYSIS & RESULTS

In this analysis, we used the data obtained by LAT between 2008 August 4 and 2010 Decem-

ber 23. The *Fermi* Science Tools v9r18p6 package is used to reduce and analyze the data in the vicinity of HESS J1745-303. Only the events that are classified as class 3 or class 4 are adopted. The post-launch instrument response functions “P6_V3_DIFFUSE” were used throughout this investigation.

With the aid of the task *gtlike*, we performed unbinned maximum-likelihood analysis for a circular region-of-interest (ROI) with a 10° diameter centered on the nominal position of HESS J1745-303 (i.e. RA= $17^h45^m1.999^s$ Dec= $-30^\circ22'12.0''$ (J2000)). The size of ROI have been chosen to avoid the surrounding bright sources so as to reduce the systematic uncertainties due to the inaccurate background subtraction in this complex region. For subtracting the background contribution, we included the Galactic diffuse model (gll_iem_v02.fit) and the isotropic background (isotropic_iem_v02.txt), as well as 41 sources in the first *Fermi*/LAT catalog (1FGL; Abdo et al. 2010) within 10° from the aforementioned center.

To begin with, we compared the spectral properties inferred by LAT and EGRET. For a consistent comparison with Hartman et al. (1999), we used events with energies > 100 MeV for our initial analysis. We assumed a power-law (PL) spectrum for HESS J1745-303 as well as all 1FGL sources in our consideration. All the sources are assumed to be point sources throughout this investigation. The best-fit model yields a photon index of $\Gamma = 2.16 \pm 0.03^5$ and a test-statistic (TS) value of 499 which corresponds to a significance of 22σ . This is consistent with the significance reported in the preliminary analysis by Chernyakova et al. (2011). The photon index is found to be consistent with 3EG J1744-3011 (i.e. $\Gamma = 2.17 \pm 0.08$). To further compare with the EGRET results, we compute the integrated photon flux in $0.1 - 10$ GeV which is found to be $2.06^{+0.24}_{-0.23} \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$. This is ~ 3 times smaller than that of 3EG J1744-3011 (i.e. $6.39 \pm 0.71 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$). The discrepancy can be due to the improved spatial resolution of LAT, and hence the estimation of background contribution from the nearby sources is more accurate than EGRET.

Considering the background, as HESS J1745-

⁵All errors quoted in this paper are statistical only and are computed for a confidence interval of 1σ .

303 is located close to the Galactic center where the diffuse γ -ray emission is very intense, the contamination can possibly be large at lower energies. Also, the point spread function (PSF) of LAT is narrower at higher energies. While the 68% containment radius at 100 MeV is $\sim 4.5^\circ$, it is only $\sim 0.8^\circ$ at 1 GeV.⁶ Therefore, the contamination due to the PSF wings of the nearby sources can also be minimized by limiting the analysis at higher energies. In order to minimize the systematic uncertainty in the background modeling so as to obtain robust results, we restricted the subsequent analysis in 1 – 20 GeV. In this adopted band, the best-fit PL model results in a TS value of 332 which corresponds to a detection significance to be $\sim 18\sigma$. To examine the robustness of the detection, we have also considered the systematic uncertainty of the Galactic diffuse emission background. Following Abdo et al. (2010), we repeat the analysis by varying the slope and the normalization of the Galactic diffuse model in 0 – 0.07 and $\pm 10\%$ respectively. Within the uncertainty of the background model, the detection significance remains over 10σ . This best-fit PL model yields a photon index of $\Gamma = 2.60 \pm 0.05$ and an energy flux of $5.25^{+1.87}_{-1.47} \times 10^{-11}$ ergs cm $^{-2}$ s $^{-1}$ in 1 – 20 GeV. The best-fit PL model and the γ -ray spectrum as seen by *Fermi* LAT is shown in Figure 1.

Besides a simple PL model, we have also examined if a broken power-law (BKPL) or an exponential cutoff power-law (PLE) can describe the spectrum better. The fittings with BKPL and PLE results in the TS values of 335 and 333 respectively. Based on the likelihood ratio test, the additional spectral parameters in BKPL/PLE are not strongly required which suggests that a single PL is statistically sufficient to describe the data. For the PLE model, the best-fit photon index and cut-off energy are $\Gamma = 2.31 \pm 0.07$ and $E_{\text{cutoff}} = 12.63 \pm 4.69$ GeV respectively. On the other hand, for the BKPL, the initial fitting resulted in a break energy and the photon indices of $E_{\text{break}} = 3.68 \pm 0.22$ GeV, $\Gamma_1 = 2.32 \pm 0.15$ and $\Gamma_2 = 3.09 \pm 0.26$ respectively. However, different from the best-fit solutions inferred from PL and PLE models, we found that the solution inferred from the BKPL fit is unstable subjecting to the

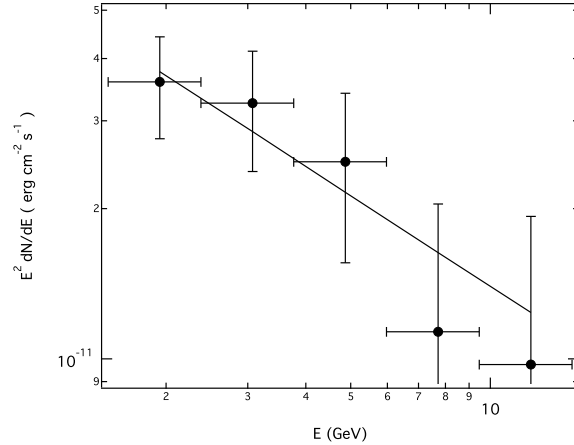


Fig. 1.— *Fermi* LAT spectrum of HESS J1745-303. The solid line represents the best-fit power-law model.

perturbations in the parameter space. In view of the problem of the convergence, we will not further consider BKPL model in all subsequent analysis.

Although the extra parameter, E_{cutoff} , in the PLE model is not statistically required, one is not able to completely rule out it in view of its capability in depicting the observed data. As a PLE model typically describes the γ -ray spectrum of a pulsar (Abdo et al. 2010b, 2011), we speculate if there is any hidden pulsar in HESS J1745-303. To test this hypothesis, we have performed a blind search for coherent pulsation. The arrival times of each photon were barycentric corrected with the nominal position of HESS J1745-303 adopted. To minimize the impact due to the ignorance of the spin-down rate, we have divided the full time span of the adopted data into 5 segments and run the Fourier analysis in each segment independently with the aid of the tool *gtpspeak*. From each computed power spectrum, we picked out 10 peaks and investigated if there is any correlation among different segments. However, we did not identify any promising periodicity candidate in this data. Hence, we conclude that there is no evidence for a hidden pulsar in HESS J1745-303.

As 3EG J1744-3011 was reported to be a variable (Torres et al. 2001), we also examine the variability with LAT data. First, we extracted the light curve obtained from the data within 1° from the nominal position of HESS J1745-303 with

⁶For updated status, please refer to http://www.glast.slac.stanford.edu/software/IS/glast_lat_performance.html

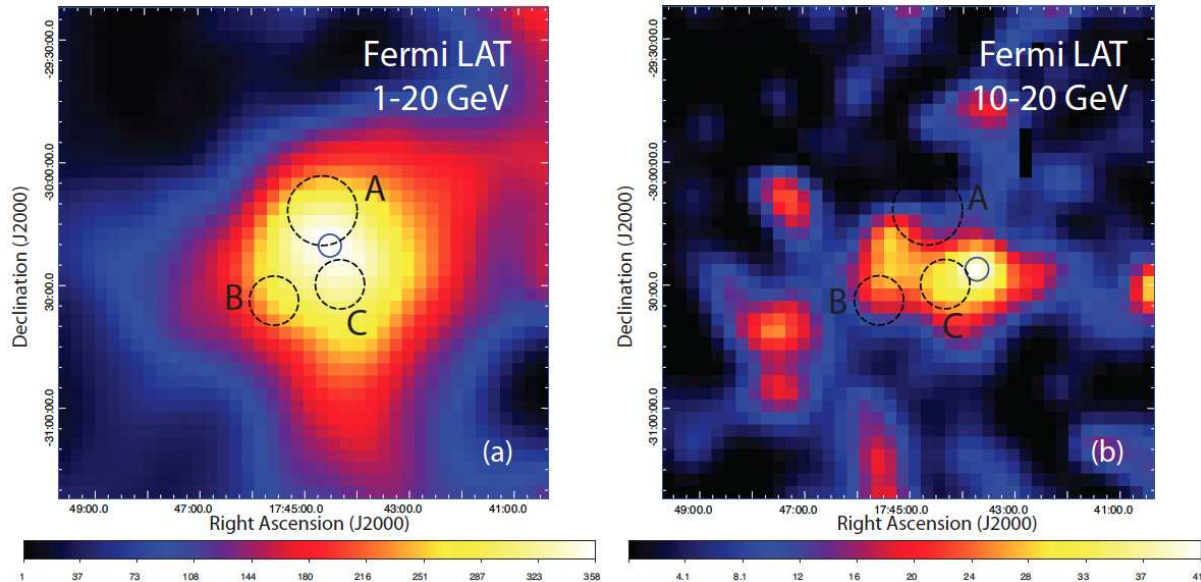


Fig. 2.— (a) Test-statistic (TS) map in 1 – 20 GeV of a region of $2^\circ \times 2^\circ$ centered at the nominal position of HESS J1745-303. The color scale that used to indicate the TS value is shown by the scale bar below. The blue circle represents the 1σ positional error circle determined by *gtfindsrc*. Various TeV emission components of HESS J1745-303 (i.e. regions A, B and C in Fig. 1 of Aharonian et al. 2008) are illustrated by the black dashed circles. (b) Same as Fig. 2a but in the energy range of 10 – 20 GeV.

a binning factor of 10 days in the energy range of 1 – 20 GeV. By fitting a horizontal line to the light curve, we obtain a reduced chi-square of $\chi^2_\nu = 1.5$ for 87 degrees of freedom. Hence, there is no strong evidence for any variability or flaring.

For a further investigation of the possible spectral and flux variability, we divided the whole data into five segments of equal time span and performed an unbinned likelihood analysis on each segment. The results are summarized in Table 1. A simple PL was adopted for all the fittings. Within the tolerance of the statistical uncertainties, we conclude that neither the spectral shape nor the flux varies among these segments.

We have computed the $2^\circ \times 2^\circ$ TS map in 1 – 20 GeV centered at the nominal position of HESS J1745-303 by using the tool *gttsmap*. This is displayed in Figure 2a. Utilizing *gtfindsrc*, we determined the best-fit position in 1 – 20 GeV to be RA=17^h44^m31.440^s Dec=−30°20′32.28″ (J2000) with a 1σ error radius of 0.05° . The position locates between regions A and C of HESS J1745-303. Given that the PSF has a 68% containment radius

of $\sim 0.8^\circ$ at 1 GeV, the source extent inferred in this band is consistent with that of a point source. The relatively wide PSF do not allow us to determine whether GeV emission is associated with any particular TeV feature. To further examine the spatial nature, we also computed the TS map in 10 – 20 GeV which is displayed in Figure 2b. Since the 68% containment radius at 10 GeV is ~ 4 times smaller than that at 1 GeV, the feature can be better resolved. We found that the peak TS value found in this band is 41 which corresponds to a significance of $\sim 6\sigma$. Within the systematic uncertainty of the Galactic diffuse background, we found that the detection significance of the source remains over 4σ in this band. The best-fit position in 10 – 20 GeV is found to be RA=17^h43^m44.160^s Dec=−30°26′24.00″ (J2000) with a 1σ error radius of 0.05° . This differs from that inferred in 1 – 20 GeV by 0.2° . We note that the GeV feature found in this hard band is apparently peaked at region C and possibly extended to region B. Although it appears to be extended in the hard band, the relatively low detection significance in this energy range does not allow a firm conclusion.

TABLE 1

 γ -RAY SPECTRAL PROPERTIES AND ENERGY FLUXES OF HESS J1745-303 AT DIFFERENT EPOCHS.

Time segment Mission elapsed time (s)	Γ	$f_{\gamma}^a(1-20 \text{ GeV})$ $10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$
239557417–254601478.2	2.67 ± 0.23	$4.45^{+12.93}_{-3.96}$
254601478.2–269645539.4	2.45 ± 0.18	$6.65^{+14.28}_{-5.36}$
269645539.4–284689600.6	2.57 ± 0.05	$5.73^{+2.22}_{-1.7}$
284689600.6–299733661.8	2.70 ± 0.25	$5.02^{+16.15}_{-4.60}$
299733661.8–314777723	2.80 ± 0.30	$4.35^{+19.16}_{-4.28}$

^aThe quoted errors of energy have taken the statistical uncertainties of both photon index and prefactor into account.

3. DISCUSSION

In this paper, we have reported a detailed study of HESS J1745-303 with *Fermi* LAT data which provides a missing piece in understanding the nature of this dark accelerator. In view of the putative variability of 3EG J1744-3011, Aharonian et al. (2008) argued that the GeV counterpart is unlikely to be associated with HESS J1745-303. However, we do not find any evidence for the spectral/flux variability from the LAT data. The discrepancy of the LAT result and that inferred from EGRET is most likely due to the differences between their instrumental performance. With the improved angular resolution and sensitivity of LAT, many previously unknown sources in the proximity of HESS J1745-303 are now detected. As several sources within $\sim 2^\circ$ are found to be variable, including 1FGL J1747.2-2958 which is the γ -ray counterpart of PSR J1747-2958 (Abdo et al. 2010), the source confusion in the EGRET data can possibly lead to the apparent variability.

It is interesting to compare the spectral properties inferred in the GeV regime with those obtained by H.E.S.S.. First, the photon index inferred from the LAT data (i.e. $\Gamma = 2.60 \pm 0.05$) is similar to that inferred in TeV (cf. Tab. 2 of Aharonian et al. 2008). Furthermore, the extrapolated photon flux in 1–10 TeV with the best-fit PL model is found to be $(2.21^{+1.84}_{-1.03}) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ which is consistent with any individual spatial component observed by H.E.S.S. within 1σ uncertainties (cf. Tab. 2 of Aharonian et al. 2008).

Since the TeV spectral data of region A is avail-

able (cf. Fig. 2 of Aharonian et al. 2008)⁷, we further compare this particular region with the GeV spectrum by constructing a spectral energy distribution (SED) which is display in Figure 3. Both data can be simultaneously fitted with a single PL of $\Gamma = 2.63 \pm 0.03$. This clearly demonstrates that the TeV spectrum of this spatial component can be smoothly connected to the GeV spectrum.

For regions B and C, despite that no TeV spectral data is currently available, we note that their spectral shapes reported by Aharonian et al. (2008) are similar to that of region A. Within the statistical uncertainties of the spectral properties inferred in both GeV and TeV regimes, the TeV spectra of these regions can also be possibly connected to that of GeV. Further investigation by H.E.S.S. is strongly encouraged, particularly for region C as most of the γ -ray emission in 10–20 GeV apparently coincides with this spatial component.

As both PL and PLE model can describe the GeV spectrum equally well, we cannot discriminate these competing models based on the current data. In view of the exponential cut-off, the spectral connection between the GeV and TeV regimes cannot be established with the PLE model. However, we would like to point out that the best-fit cut-off energy, $E_{\text{cutoff}} = 12.63 \pm 4.69 \text{ GeV}$, falls in the highest energy bin of the LAT spectrum (cf. Fig. 1 and Fig. 3). Owing to the small photon statistics in the hard band, the statistical uncertainty of the highest energy bin is rather large.

⁷<http://www.mpi-hd.mpg.de/hfm/HESS>

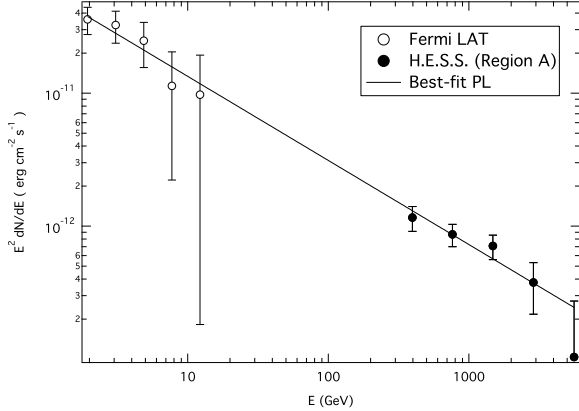


Fig. 3.— Spectral energy distribution of HESS J1745-303 as observed by *Fermi* LAT and H.E.S.S. The H.E.S.S. spectrum is for region A. The solid line represents the best-fit power-law model inferred in the joint analysis of both data sets.

In view of this, it remains unclear whether the inferred cut-off is genuine as this particular data point is sensitive to the systematic uncertainty of the background. Analysis of the LAT data in higher energies (e.g. $\gtrsim 10$ GeV) with sufficient photon statistic in the future can help to discriminate these two models.

The detection of γ -rays provides a strong evidence for the particle acceleration. It should be noted that there are two SNRs and two pulsars around HESS J1745-303 which can be the potential high energy particle injector (cf. Fig. 1 of Aharonian et al. 2008). Based on the small distances of G359.0-0.9 and PSR B1742-30, Bamba et al. (2009) argued that these two sources are foreground objects which are unrelated to HESS J1745-303. With the GeV counterpart revealed by LAT, we can now safely rule out the possibility that PSR B1742-30 is the major contributor as its spin-down flux, $\dot{E}/4\pi d^2 \sim 10^{-11}$ erg cm $^{-2}$ s $^{-1}$, is lower than the energy flux observed in the GeV regime (cf. Manchester et al. 2005). On the other hand, for PSR J1747-2958, the sum of γ -ray flux of 1FGL J1747.2-2958 and HESS J1745-303 observed by LAT only consumes $\sim 5\%$ of its spin-down flux ($\sim 3 \times 10^{-9}$ erg cm $^{-2}$ s $^{-1}$). Therefore, it is energetically possible to be the source for the high energy particles. Nevertheless, with its east-

ward proper-motion (Hales et al. 2009), its backward extrapolated position by its spin-down age is found to have an offset of $\sim 0.6^\circ$ and $\sim 0.8^\circ$ from the best-fit positions inferred in 1 – 20 GeV and 10 – 20 GeV respectively. If the feature found by H.E.S.S. and LAT is indeed a PWN, then it is one of the most peculiar system because of its large positional offset with respect to the pulsar position.

While the contribution of PSR J1747-2958 is uncertain, the interaction between the shock from G359.1-0.5 and a molecular cloud in its neighbourhood is considered to be a more viable means to produce the observed γ -rays. For both hadronic and leptonic scenarios, Bamba et al. (2009) have modeled the broadband spectrum of the region A of HESS J1745-303. However, comparing Fig. 1 in this paper and Fig. 5 & 6 in Bamba et al. (2009), the GeV flux predicted in all the scenarios considered in their work are at least an order of magnitude lower than that observed by LAT. Revised theoretical investigation with constraints provided by LAT is therefore required. Moreover, while the other known systems of SNRs interacting with molecular clouds have their remnant shells found in other wavelengths coincided with the γ -ray emission (e.g. Castro & Slane 2010; Abdo et al. 2010c), there is no such evidence for HESS J1745-303. We should point out that all the previous multiwavelength campaign were targeted only at the bright component of HESS J1745-303, namely the region A. Since the LAT observation suggested that the GeV emission can possibly be originated from the regions C/B, observational investigations aim at these regions are encouraged for a further understanding of this mysterious object.

Based on the above discussion, we have to admit that the energy injection source of HESS J1745-303 remains unclear. It is instructive to compare it with other nearby high energy sources. Aharonian et al. (2006b) have reported observations of an extended region of very high energy (VHE, > 100 GeV) γ -ray emission correlated spatially with a complex of giant molecular clouds in the central 200 pc of the Milky Way. It appears that TeV emissions from the molecular clouds in the vicinity of the Galactic Center are quite common phenomena. In addition, similar to the case of HESS J1745-303, 6.4 keV lines have been commonly detected from many molecular clouds near

the Galactic Center, e.g. Sgr B2 (Koyama et al. 1996; Murakami et al. 2000), Sgr C (Murakami et al. 2001) and others (Bamba et al. 2002; Predehl et al. 2003; Nobukawa et al. 2008; Nakajima et al. 2009; Koyama et al. 2009). It has been speculated that these neutral iron lines arise from the reflection by the dense molecular clouds which are irradiated by the nearby X-ray sources (e.g. Koyama et al. 2007; Inui et al. 2009). On the other hand, Dogiel et al. (2009) argued that these 6.4 keV lines from the molecular clouds are excited by a background intensity of subrelativistic protons coming from the escaped part of a past captured star by the Galactic supermassive black hole Sgr A*. The periodic stellar capture events may explain the recent observed *Fermi* bubble (Cheng et al. 2011a). This subrelativistic proton wind can also form shock by hitting the clouds and produce relativistic protons. It is shown that the decay of neutral pions produced by hadronic collisions between the accelerated relativistic protons in the clouds can emit a power-law γ -ray spectrum from 30 MeV to 10 TeV without any spectral break (Cheng et al. 2011b in preparation). If this is true, then the high energy emission from various molecular clouds in the vicinity of the Galactic center are correlated to the past activities of the Galactic center and their intensity might be correlated with the propagation history of the injection of these subrelativistic protons escaped from the capture past events.

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